ARTIFICIAL FERTILIZATION OF LAKES AND PONDS

A Review of the Literature

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PREFACE

One of the primary factors limiting the productive capacity of a body of water is the quantity of available nutrients which form basic materials for structure and growth of living organisms. Fertilization techniques attempt to supply these nutrients in optimal quantities, thereby overcoming natural chemical deficiencies and shifting limitations of productivity to other factors. Aquatic fertilization is as ancient as pisciculture. The Chinese reputedly fertilized carp ponds more than 2,000 years ago, developing the process as an art rather than as a science. Through the intervening years, culture-pond enrichment apparently existed as an offspring of agronomy, but recent scientific work has shown that the two fertilization processes (agricultural and aquicultural) are not homologous because of differences in the very nature of land and water. Aquatic fertilization undoubtedly has merit in raising productive levels, else it could not have survived to the present state of development.

Artificial aquatic enrichment has been limited mainly to standing water, but a few reports on brackish water and stream fertilization have appeared in the literature. Huntsman (1948), for example, succeeded in increasing the abundance of plants and numbers of fish in a Nova Scotian stream with inorganic fertilizers. Admittedly, the barren state of the stream provided an excellent background for the experiment. However, these few isolated reports of stream enrichment have been largely trial and error, and do not provide sufficient information for adequate treatment of the subject. A great deal remains to be learned about the enrichment of standing water before a sound approach can be made to the fertilization of lotic habitats. Therefore, the following report concerns only lenitic fresh water and the complexities that relate to its artificial enrichment.

INTRODUCTION

The three essentials for protoplasmic growth are light, heat, and raw materials. Natural enrichment, the source of raw materials, occurs to a certain degree in every body of water, by decomposition of organic matter produced within the environment, by ion exchanges between water and sediments, and by nutrient increases from affluents carrying minerals and humus leached out of the surrounding soils. Artificial fertilization, an accessory to these natural proccesses, is a human-controlled operation concerned with the addition of natural or manufactured fertilizers and directed toward the increased production of fish.

Artificial fertilization is by no means a simple process. Consideration must be given to the conditions and variables of the environment which affect both procedure and results of fertilization. Such environmental complexities are presented in this report by assembling information which occurs in fish cultural and limnological literature. The objective is to show how and where artificial enrichment applies to the present culture, management, and investigation of fresh-water fisheries in this country. No effort has been made to advise or outline a method of fertilizing; the intent is to minimize meaningless trial-and-error experiments by giving the investigator a grasp of the complex nature of the subject. The literature reviewed is essentially North American, but certain Asiatic and European reports are included. These European reports represent a composite of vast European knowledge, and frequent references will be made to them.

Early appearance of pond-culture fertilization in scientific literature dates back to European work in the late nineteenth century. Davis and Weibe (1930) and Smith (1934a) reviewed the publications of their predecessors in this field, and Neess (1949) presented a historical synopsis of European pond culture. These summaries indicated that the first European experiments were directed toward the production of plankton and were later applied directly to carp culture. American work began in a similar fashion (Embody, 1921; Wiebe, et al., 1929; Wiebe, 1930). As a scientific procedure, early enrichment experiments had one fault in common; they proceeded from the nutrient addition to fish or fish-food production disregarding fundamental physical, chemical, and biological factors which, directly or indirectly, influence enrichment and the resultant changes in productivity. Cognizant of this, some more-recent investigators have conducted experiments of greater significance. Nevertheless, there exists an incomplete understanding of fertilization dynamics which can be supplemented only by careful experimentation.

FUNDAMENTALS OF AQUATIC FERTILIZATION

Numerous factors, inherent in the metabolism of fresh water, concern the process and outcome of artificial fertilization. They may be classified as physical, biological and chemical, but this grouping is made only to facilitate discussion. In practice it is necessary to consider such things as they actually exist - highly interrelated. Moreover, few factors remain constant within a given body of water. The variability and interaction of these factors present basic problems in the understanding and success of aquatic fertilization.

Physical Considerations

Reference to physical factors in literature is abundant but fragmen-

tary. Schaeperclaus (1933) treated the important physical factors in pond culture, particularly depth. He established optimum depth for assimilative plant functions at 1 to 2 meters, since shallower areas fluctuate readily in temperature and oxygen content. Schaeperclaus further pointed out the increased nutrient release from bottom soils per unit water volume in shallow waters, and in ponds with large shore development. Rounsefell (1945) indicated a straight-line logarithmic relation between fish productivity and size of water bodies; smaller lakes had the greater yield per unit area. Rate of water exchange was considered by Schaeperclaus (1933), Lawson (1937), Wiesner (1937), and others, who concluded that a small exchange is usually necessary for temperature and oxygen control, but that a large outflow removes nutrient materials. Nutrients may also be lost by seepage or by settling through sandy or rocky bottom types, which are noticeably unproductive (Lawson, 1937; Province of Quebec, 1948). Many authors discuss light and heat requirements as affected by shade and turbidity of the water.

In all waters, light and heat are the physical essentials for photosynthetic activity which, in turn, is basic to productive capacity. Water temperatures, in general, depend upon climate, sunlight, and depth. Probst (1950) found an average increase in carp yield of 22 kilograms per hectare for each 1° C. rise in mean temperature in unfertilized ponds over a period of 32 years. Light intensity and penetration are affected by border vegetation, floating aquatic plants, and turbidity. The latter may be caused by plankton blooms, silt, particulate organic matter, or by pigments and suspensoids as in bog waters. Excessive turbidity, according to Smith (1934a), has a pronounced effect in confining daily heat gains to the surface layer of water. Plankton turbidity, while often indicative of productive waters, limits heat and light penetration, thus reducing the depth and effective volume of the trophogenic zone. On the other hand, such turbidity aids in the control of soft water flora (Surber, 1948; Swingle and Smith, 1950) and improves angling success (Smith and Swingle, 1943). Excessive shade caused by aquatic plants is a similar hindrance to heat and light exposure of the water and results in lowered production (Wiesner, 1937). Temperatures, optimum for growth of the desired fish species, plus time give the growing season which is also relevant to fertilization. Lastly, water movement can be added inasmuch as it affects the distribution of heat and nutrient materials within the environment.

Generalizations may be drawn concerning the physical characteristics of waters with respect to fertilization:

1. Dimensional increase of the environment (beyond that of the highly productive culture pond) decreases its possibility for successful fertilization. This limitation involves economical impracticability, lack of control and manipulation, and chemical-biological complexities which will be considered in the following text.

2. Increasing depth decreases the relative productive potential.

3. Geographical locations having mild climates and long growing seasons are most favorable for enrichment because of temperature and light factors.

4. Heat and light are essentials that may be regulated to some extent by control of border and surface vegetation.

5. Turbidity, other than that caused by plankton, is undesirable. Plankton turbidity is a consequence of the productive metabolism of water and may sometimes be of value.

6. Rate of water exchange should be at a minimum.

7. The nature of the bottom affects nutrient loss and productive ability.

Biological Considerations

The organisms in an aquatic habitat, relative to fertilization and productivity, were discussed in some detail by Schaeperclaus (1933). His interpretation of the biological complement, with modification, placed the important flora and fauna in three groups: 1. Basic producers (bacteria, water molds, phytoplankton, soft waterflora and microfauna); 2. Intermediate consumers (zooplankton, insects, and other benthic fauna); 3. Ultimate consumers (fish). Wiesner (1937) referred to the binding of nutrient elements by organisms as "biological absorption", while Meehean (1935), Lawson (1937), Smith and Swingle (1940), and others indicated the importance of bacteria and higher flora acting in that capacity Plants also act as a storehouse for nutrient elements (Surber, 1947). Invertebrate fauna links flora to fish in the simplified nutrient chain (Lawson, 1937; Smith and Swingle, 1940), but all organisms are not beneficial to the productive cycle. Nutrients may be lost temporarily or permanently through the action of denitrifying and sulfate-reducing bacteria (Lawson, 1937; Zuur, 1952), blue-green algae (Hasler and Einsele, 1948), and emergent aquatic plants (Wiesner, 1937). Excessive growth of soft waterflora may tie up nutrients, crowd the water, or cause anaerobiosis upon decay (Wiebe, 1934; Meehean, 1935).

These organisms may be considered, to great advantage, in the pattern of a food chain, or succession of biota from nutrients to removable crop. Meehean (1933) proposed alternative food chains in black-bass culture, and later (Meehean, 1934) outlined a more simplified chain terminating with bass fingerling:

```
Organic                    Protozoa
Fertilizer --> Bacteria --> Rotifera --> Zooplankton  --> Chironomids
                           Nauplii      (as Daphnia)      Ostracods
                               ↘                          ↙
                           Bass fry --->        Bass fingerling
```

Three food chains of differing natures were described by Smith and Swingle (1940):

Phytoplankton) Small organisms)	(Golden shiner (Gizzard shad (Goldfish		
Bacteria) Phytoplankton)	(Zooplankton) (Insect larvae)	(Bluegill (Small crappie (Small bass	
Bacteria) Microfauna)	(Plankton) (Insects)	( ) (Small fish)	(Large crappie (Large bass

These examples are given to illustrate some approaches taken in considering the biological fate of nutrients. Ball (1949) concluded that food habits (of fish) nearer the base of a food chain result in a greater increase of fish. It thus seems axiomatic that shorter food chains result in larger and more consistent fish returns. The cyclic behavior of populations is another important characteristic of aquatic life closely related to the succession discussed above. This advance and decline of numbers is most pronounced among the lower organisms, and may take an erratic pattern. The nature of such fluctuations is not well understood, but it should be remembered that they may occur independent of nutrient addition.

Final consideratior is given to productivity in which the entire concept of fertilization is embodied. The objective of artificial enrichment is to increase the productive capacity of a body of water and so increase the potential yield of fish. Each environment differs in the amount of living matter it is able to support. Lawson (1937) believed that superior production is based on abundant microvegetation. Productive differences among waters are characterized by many factors. Wunder et al. (1935) stated that good producing ponds have algal blooms in spring or early summer, and that these blooms are continuous in the best producing ponds. Various indexes of productivity are treated in another section, but it may be stated at this point that the ultimate measure is the yield of desirable fish per unit area and time. This productive capacity is realized only when the crop is removed. Fertilization places nutrients in the water and productive anabolic processes transform them into fish flesh. It follows that an expenditure of time and energy on fertilization will be profitable only if the water is cropped and the fish utilized.

Chemical Considerations

The chemical aspect of the aquatic environment is, by far, the most important consideration involved in the fertilization process. A brief description of the chemical nature of lakes and ponds will later aid in the understanding of nutrient interactions. The aquatic habitat can be thought of as a quantity of water retained in an earthen bowl. The re-

taining structure contains mineral and organic matter as solid substances which, by chemical and biological actions, influence the composition of the water. In addition to this, Neess (1949) pointed out the function of the bottom colloidal fraction (humic substances, ferric gels, clay) which absorts and regulates the distribution of certain soluble nutrients, and also facilitates chemical decomposition and transformation by microorganic life occurring therein. As in agriculture, fertile soils are indicative of high productivity. Schaeperclaus (1933), Meehean (1935), and Lawson (1937) discussed the quality of the substrate. The bottom, at least in shallow water, acts as a nutrient storehouse, center of biological activity, and area of chemical transformations. Topsoil, and soils rich in humus, are most desirable. Marl, clay, sand, and rock follow a general order of decreasing richness. The water contains dissolved gases and solids, and suspended particulate matter, which are in continuous exchange with the substrate. Oxygen and carbon dioxide are gases most abundant and vital to life processes. Methane, hydrogen, nitrogen, ammonia, and hydrogen sulfide may be present in small quantities. The last three gases and carbon dioxide may be toxic in large amounts. Suspended solids can be divided into organic (as detritus) and inorganic (silt) components. Dissolved solids comprise a wide range of compounds containing most elements that are in some way soluble in water. These are also inorganic, or complex organic, compounds. A certain proportion of each compound, depending upon its chemical characteristics, and those of the solvent, exists as ions in dissociation; this in turn affects pH, chemical reactions, and nutrient absorption.

The hydrogen-ion concentration (pH), a result of many obscure chemical conditions, is one of the singularly significant factors affecting aquatic productivity. Both soil and water should show an alkaline reaction (Wiesner, 1937). Smith (1933) found the decomposition rate of fish meal noticeably lowered above pH 9.0. Schaeperclaus (1933) termed pH 9.0 the alkaline danger point, and further recommended raising the pH of waters rated 6.5 or lower. It is well known that acid waters are poor producers. The optimal range of pH can thus be established at 7.0 to 8.5. To maintain a constant pH, water and soil must show a buffering action caused by the presence of calcium and magnesium carbonates. Schaeperclaus (1933) and Wiesner (1937) regarded this buffer action as the acid combining capacity (A.C.C.) of the water. The A.C.C. (corresponding to our methyl orange alkalinity) is the number of cubic centimeters of 0.1 N hydrochloric acid that can be neutralized by 1 liter of water. Waters of 2 to 5 A.C.C. vary only slightly in pH and are rated as "very productive."

The next step is to relate chemical nutrients to aquatic organisms. Liebig's law of the minimum, directed toward plant crops, has also been applied to fish crops. It states, in essence, that plants require certain nutrients; the presence of any one in minimal quantity will lower the total productivity. Early work in nutrient enrichment carried the results of agriculture to aquiculture. From its inception to the present time, aquatic fertilization has dealt almost exclusively with organic matter and four chemical elements: nitrogen, phosphorous, potassium, and

calcium. These substances were added to the water in quantities that yielded the most fish. This approach proved successful in pond culture; consequently, little consideration was given to the action of these nutrients or to the many other elements essential to living matter. It was realized some years ago that nitrogen and potassium were not always needed. Davis and Wiebe (1930) presented the European opinion that fertilization with nitrogen and potassium is varied in effect, but all agree to the importance of phosphorus. Smith (1932a) found that plankton production varied directly with nitrogen and phosphorus concentrations, but irregularities occurred when nitrogen was used alone. Recently, Zeller[1/] concluded that only phosphorus fertilizers need be used in Missouri ponds. While this is far from a complete picture of the work that has been done, it illustrates the need for a more fundamental approach to the study of chemical enrichment.

Wiesner (1937) listed 17 elements necessary to formulate and sustain life. Grouped in order of decreasing importance, they are: oxygen, hydrogen, carbon, nitrogen; sulfur, phosphorus, sodium, potassium, calcium, magnesium, iron, chlorine, fluorine, silicon, manganese, iodine, and arsenic. Most of these appear in the environment as compounds of two or more elements. Optimum ranges of some compounds have been established for certain organisms. Moyle (1945), for example, was able to distinguish three groups of aquatic flora in Minnesota lakes: Hardwater flora (in waters with alkalinity between 90 and 250 parts per million, sulfate below 50 parts per million, pH from 8.0 to 8.8); Soft-water flora (in waters with alkalinity below 40 parts per million, sulfate below 5 parts per million, pH below 7.4); and sulfate-water flora (in waters with alkalinity greater than 150 parts per million, sulfate usually above 125 parts per million, pH from 8.4 to 9.2). Knowledge of the minimum threshold requirements of organisms for various elements is nonexistent, except for indications that they are extremely low. What, then, is known about the individual elements in fresh-water metabolism?

The apparent success of phosphorus as a fertilizer has made it the center of interest and experiment. Its main physiological function is to assimilate nitrogen into cellular matter (Hasler and Einsele, 1948). Water phosphorus occurs in small quantities (usually less than 1 milligram per liter) as organic and phosphate fractions (Welch, 1935). The organic component is further divided into soluble organic and sestonic phosphorus. Many experiments have shown that added phosphate disappears rapidly from the water, usually within a week or two. Zeller's (1953) work indicated a storage of phosphorus in cells during periods of abundance with a later growth at the expense of stored material; he also found a constant increase of phosphate in pond bottoms, and attributed this to insolubility and settling of fertilizers. Hasler and Einsele (1948) indicated a rapid regeneration of sedimented phosphorus in littoral

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1/ Zeller, H. 1952. Inorganic nutrient levels in fertilized and unfertilized farm ponds in central Missouri. Master's Thesis, Univ. Mo., 145 pp.

areas, and the possible permanent loss of it in hypolimnetic depths. Although insoluble phosphorus accumulates mainly at the bottom. this is also the region of greatest phosphorus solubility (Neess, 1949). Soluble phosphorus is highly motile, enabling it to form insoluble compounds with calcium and iron (Lawson, 1937; Wiesner, 1937; Hasler and Einsele, 1948; Neess, 1949).

A study by Barrett (1953) indicates that the rate of disappearance for added phosphorus from epilimnial water was related to alkalinity (theoretical lower limit of alkalitrophy seemed to be between 120 and 160 parts per million M.O.A.), and also that the amount of exchangeable phosphate in bottom sediments was inversely related to the ratio of marl to organic matter. Added phosphorus accumulated in the hypolimnion or sediments in the following situations: In lakes where sediments were high in organic matter and low in marl, phosphorus was adsorbed by sediments and remained in an exchangeable form; where sediments were high in both marl and organic matter, phosphorus accumulated in hypolimnetic water and sediments; where sediments were very low in organic matter and very high in marl, phosphorus did not accumulate in hypolimnetic water nor was it adsorbed by sediments, but probably became fixed in insoluble precipitates.

Recent experiments with radioactive phosphorus (P^{32}) in stratified lakes have furthered the understanding of phosphorus metabolism and perhaps the action of other elements. McCarter et al. (1952) traced the movements of P^{32} in a lake after introducing it below the thermocline. Lateral movement, quite pronounced in the direction of the outlet, averaged 3 meters per day. Vertical movement was slight and penetration of soluble phosphorus above the thermocline was not evidenced. Hutchinson and Bowen (1950) expressed the opinion that most of the added phosphorus enters phytoplankton. The leaves and stems of some aquatic plants absorb P^{32} before it enters the root system, according to Hayes et al. (1952). Coffin et al. (1949) studied living organisms more closely to find absorption of P^{32}occurring in a matter of minutes and hours. Plants and microorganisms absorbed phosphorus directly. Zooplankton obtained it either directly, or indirectly by feeding on smaller organisms. Fish apparently acquired P^{32} by feeding upon plankton and similar organisms. Recent experiments have indicated that fish may absorb phosphorus and other nutrient substances directly from water. These authors further found that zooplankton could concentrate phosphorus up to 40,000 times the level present in surrounding water. An average of concentration ratios, given for several aquatic plants and animals, showed that the floral level of phosphorus was about 250, and the faunal level about 20,000 times the water content.

Hutchinson and Bowen (1950) postulated a steady exchange between organic and phosphate phosphorus, and described rapid gains of P^{32} by the hypolimnion in terms of seston sedimentation. They concluded that P^{32} replacement in the epilimnion occurred each 3 weeks. Hayes et al. (1952) proposed quantitative exchanges of phosphorus between the soluble

and solid (including living matter) fractions. In their experiments, the turnover time for soluble P^{32} was 5.4 days, and 39 days for the P^{32} in solids. Less than one-sixth of the added phosphorus was in solution at any one time. Considering the results of other experiments, these workers calculated turnover times for phosphorus in solids up to 176 days, and for dissolved phosphorus to 30 days. From 4.7 to 8.7 times as much phosphorus was turning over as was in solution. McCarter et al. (1952) analyzed the hypolimnetic muds and concluded that the P^{32} had not penetrated much beyond 1 millimeter.

The phosphorus picture can be reduced to greater simplicity:

1. The case history of fertilization supports phosphorus as the most essential common fertilizing element.

2. Small quantities exist in natural waters, mainly in two forms, organic phosphorus and phosphate. The former is more abundant, but the latter is more active and often minimal or limiting to productive capacity. Phosphate may become bound in insoluble compounds, and this loss may be related to the alkalinity of the water and to the marl organic matter ratio of the substrate.

3. Apparently, most phosphate is absorbed directly by lower organisms and indirectly by fish which feed upon them. The direct absorption occurs in minutes or hours. Fauna can concentrate phosphorus in far greater amounts than can flora.

4. The dynamic state of phosphorus has been described. The environment has a great affinity for phosphorus, most of it rapidly entering solids. A continuous phosphorus exchange occurs between water and solids. Since the amount of phosphorus in solution is small, the turnover rate for dissolved phosphorus is more rapid than that for phosphorus in solids.

Nitrogen, as a basic constituent of protein, is necessary for the formation of living matter (Meehean, 1935). It occurs as a free element (N), or as ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), and organic nitrogen. These form a well-known cycle related to bacterial activity. Nitrification proceeds in the order named, by the action of nitrogen-fixing and nitrifying bacteria. Welch (1935) listed molds and possible algae as nitrogen fixers. Nitrate and nitrite nitrogen (especially the former) are generally accepted as the available forms of nitrogen for anabolic activity of higher organisms. Pennington (1942) found that cultures of algae and bacteria utilized ammonia nitrogen more rapidly than nitrate nitrogen. Denitrification acts in the reverse order with denitrifying bacteria changing organic nitrogen into ammonia. According to Welch (1935), free nitrogen is barely soluble and enters the water from the atmosphere. Ammonia, he stated, is highly soluble and toxic to fish in relatively small amounts (8 p.p.m.). The nitrate nitrogen content of water is low and usually variable.

Chu (1943) concluded from laboratory results that nitrogen and phosphorus occur naturally in quantities far below the upper limit for optimal growth and often do not reach lower optimal concentrations. These elements, he added, may limit growth at certain times of the year and may exert a selective influence on different species of algae when concentrations are below the lower optimal limit (nitrogen, 0.3 to 1.3 p.p.m. phosphorus, 0.018 to 0.090 p.p.m.). Such concentration limits may not apply to natural situations. Since water is exposed to unlimited quantities of atmospheric nitrogen, Neess (1949) postulated that nitrogen utilization is limited only within the aforementioned cycle, which is a system in equilibrium, and does not depend upon nitrogen addition. There is a possible inverse relation of nitrate-nitrogen and direct relation of organic-nitrogen content of water with productivity (Surber, 1947). Nitrite nitrogen and ammonia are indicators of pollution because they posses an oxygen demand (Wiebe, 1929). Aerobic conditions in the environment suppress ammonia and improve conditions for nitrification.

The value of potassium as a nutrient addendum is also questionable. Welch (1935) considered it a fixed requirement for plants in food manucature and a catalyst occurring naturally in small amounts (0.5 to 9.0 p.p.m. - Moyle, 1949). A slight acid reaction results when its compounds are added to water (Wiesner, 1937). Swingle and Smith (1939a) found that small amounts of potassium increased pond yields, but larger quantities caused no further increases. Potassium has a most favorable influence in peat, sand, and hard-bottomed ponds; in mud ponds, it inhibits hard waterflora (such as Equisetum) and favors soft waterflora (Schaeperclaus, 1933). Neess (1949) stated that results of potassium fertilization are erratic but cited an instance of increased production by use of potassium alone He concluded that the effects of potassium are indirect, selective, and partly bacteriological.

Compounds of calcium and magnesium, for the most part, function similarly in water metabolism. As an individual element, calcium is the more abundant and important of the two, often occurring naturally in large quantities. Welch (1935) considered calcium in the following roles: (1) Related to the translocation of carbohydrates; (2) an integral component of plant tissue; (3) acts to increase the availability of other ions; (4) reduces toxic effects of single-salt solutions of other elements. Its presence is obvious in some animal tissue, especially the exoskeletons of arthropods and mollusks. Magnesium, Welch stated, is a component of chlorophyll and, in some instances, acts as a carrier of phosphorus. Wunder et al. (1936) stated that magensium stimulates bacterial reduction of organic matter in the bottom. Calcium-rich waters are those draining marl and limestone soils. Schaeperclaus (1933) claimed that he had never encountered a pond too rich in calcium. Surber (1945) believed waters that acquire hardness by contact with limestone formations may foster growth of Chara that reach great density and curtail fish production. Schaeperclaus (1933) and Welch (1935) discussed the relations of calcium and magnesium to the carbon-dioxide mechanism of water in some detail. The affinity of

these elements for free carbon dioxide results in the formation of soluble bicarbonates ($CA[HCO_3]_2$) or half-bound carbon dioxide, and carbonates ($CaCO_3$) or fixed carbon dioxide. This mechanism is somewhat complex, being related to acidity, buffering, photosynthetic action, removal of decomposition products, and activation of other nutrients. Calcium may be deposited in large quantities as lime on the bottom of lakes and ponds. Mollusks and certain algae (marl-forming organisms) are important organisms functioning in this process. Calcium nutrition will be considered later in the discussion of liming.

Conflicting opinion is found in the literature on the value of iron in fresh waters. High iron content, according to Schaeperclaus (1933), is a phenomenon usually accompanying acid waters, and it presence denotes a poorly productive habitat. Wunder et al. (1936) believed ponds rich in iron and aluminum were good producers and that typically good ponds had bottom soils with autochthonous organic sediments rich in iron and manganese. General belief holds that a small amount of iron is necessary, but that large quantities are detrimental to productivity. Welch (1935) indicated that the function of iron lies in chlorophyll production, and that it possibly acts as a catalyst or oxygen carrier. The best algal growth, he stated, is in water having 0.2 to 2.0 milligrams of ferric oxide per liter, but in the absence of buffer compounds 5 milligrams per liter may be toxic. Estimation of the iron content of water may be made from the amount of ferric mud in the bottom (Schaeperclaus, 1933). The power of iron as a reducing agent accounts for its undesirable activity.

Welch (1935) briefly described the importance of several minor elements. Silicon is a structural component of diatoms and sponges, being soluble in water as silicate. Blooms of diatoms or desmids may cause high fluctuations in the content of dissolved silicon. Sodium supplements the action of potassium and may act as an antidote against the toxicity of some salts. Sulfur is necessary to protoplasm as a constituent of certain amino acids; it may occur abundantly in organic matter or combined with iron in bottom soils. Manganese is essential in minute quantities to chlorophyll-bearing plants. Zinc and copper are required by protoplasm in small amounts. The former may stimulate plant growth, but both may be toxic in large quantities. This group of elements, with the exception of sodium and sulfur, occur sparingly in natural waters, and little is known about their optimal levels or roles in water metabolism.

Organic compounds are more varied and complex than mineral substances. As previously mentioned, some of the organic matter in lakes and ponds occurs in solution. Welch (1935) discussed the composition and function of this dissolved matter. It is a mixture of many substances (carbohydrates, fats, and proteins), the most prominent being nitrogenous waste products. In natural waters the total amount of dissolved organic matter usually exceeds 10 milligrams per liter. Nutritionally, it is known that some organisms exist mainly on such dissolved material. Largest quantities of undissolved organic matter are found as humus in the substrate, reaching

the bottom via seston sedimentation and settling of plant matter. Meehean (1933) stated that crustaceans and chironomids may utilize proteins and carbohydrates directly, or through the action of bacteria and protozoa. Not only may organisms grow and multiply at the expense of organic matter, but saprophytic activity of bacteria and molds releases soluble organic and inorganic materials. Bacterial activity depends on the carbon-to-nitrogen (C:N) ratio of the parent substance, according to Meehean (1935). It is low when ratios fall below 10:1 and good when 20:1 or higher. The importance of carbohydrates and C:N ratios in nitrogen fixation has been indicated by Neess (1949). Lawson (1937) and others have pointed out the relation of productivity to the presence of organic matter and have indicated the need for it in humus-deficient waters.

The Fertilization Process

Two approaches can be made to artificial enrichment. The first, nutrient addition, is the common and accepted practice; it is what the word "fertilization" ordinarily implies. The second liberation of nutrients present, is a direct approach only in theory; it operates as a secondary effect in the former method, and has been given little substantial consideration as a separate process.

The primary concern of nutrient addition is the nature of fertilizing substances. These are readily classified into two groups: organic and inorganic fertilizers. The composition of several fertilizers, reported in the reviewed literature, is presented in table 1. Prince and Bear (1943) listed the nitrogen, phosphate, and potash content of various organic materials that are used or could be used as fertilizers. Complete current analyses of many fertilizers appear in State agriculturel publications dealing with such matters.

Organic fertilizers contain a large percentage of organic carbon in addition to many minerals. These supply most of the elements necessary for metabolic activity and are usable for overall enrichment of waters or as a source of carbon in an organic-deficient environment. Organic fertilizers may be in the form of manures, composts, commercial meal residues, or many other organic byproducts. Neess (1949) explained the advantages of meal fertilizers in terms of their high C:N ratios. Smith and Swingle (1943) found that organic fertilizers tend to crowd ponds with excessive plant growths, especially filamentous green algae (Swingle, 1947). Wiesner (1937) suggested the use of composted aquatic plants as an inexpensive, readily available fertilizer. Swingle and Smith (1950) recommended barnyard manure to clear muddy waters. Hora (1950) stated that the carbon in manures retains nitrogen for a longer period than inorganic fertilizers and ensures a sufficiency of carbon dioxide and nitrogen.

Inorganic fertilizers lack organic carbon and are available as single compounds (e. g., ammonium sulfate, sodium nitrate, potassium chloride),

Table 1. Composition of some fertilizing substances

Fertilizer	Composition
Inorganic:	
Colloidal phosphate............	25% CaO; 24% P_2O_5; 17% SiO_2; 4% Fe_2O_3; small amounts of Mn, Mg, Cl, Fl, Cr, Va and Na
Dicalcium phosphate............	35% P_2O_5; 28% CaO
Limate........................	48% CaO; 32% MgO
Lime marl.....................	80 to 90% $CaCO_3$
Limestone.....................	90 to 95% $CaCO_3$
Rhenania phosphate............	25% P_2O_5; 42% CaO
Superphosphate..	16 to 20% P_2O_5; $CaSO_4$; small amounts of Al, Si, Fe, Mg, and Fl
Thomas meal...................	13 to 20% P_2O_5;40 to 50% CaO; 8 to 9% Fe
Organic:	
Cottonseed meal...............	40% protein; 7% nitrogen; 3% P_2O_5; 2% K_2O
Sheep manure..................	2% N; 2% K_2O; 1% P_2O_5; low in proteins
Shrimp bran...................	53% organic matter; 44% protein; 7% N (exclusive of NO_3); 2% P
Soybean meal..................	61% total organic matter; 44% protein; 24% N (exclusive of NO_3); 1% P
Timothy hay...................	0.8% N; 0.6% K_2O; 0.2% P_2O_5
Aquatic plants, C:N ratio: (see Meehean, 1935)	
Ceratophyllum dermersum......	22.8:1
Potamogeton americanus........	18.6:1
P. filliformis...............	12.3:1

or commercial mixtures expressed in percentage ratios of nitrogen:phosphorus:potassium (N:P:K). There are also mineral fertilizers such as superphosphate which contain several minor elements in addition to soluble phosphorus (table 1).

Since the compositions of inorganic fertilizers are known or easily determined, they are especially adaptable where definite quantities of nutrient elements are to be applied. Swingle (1947) found that large amounts of phytoplankton grew in response to inorganic fertilization by virtue of the rapid solubility and distribution of the nutrient substances, but that carbon dioxide was limiting in ponds fertilized only with inorganic materials. In Japanese rice-paddy carp culture, Hiyama (1950) concluded that organic manures promoted more zooplankton than inorganic fertilizers. Organic and inorganic fertilizers have been successfully used in combination in many instances.

The following list, adapted from Lawson (1937), shows the relative consumption of different fertilizers in Czechoslovakian pond culture for 1935:

Lime and limestone	1,579	metric tons
Superphosphate	301	" "
Other inorganic fertilizers.	86	" "
Manures.	463	" "
Compost and aquatic plants	850	" "

If such a tabulation were available for fertilizers used in this country, it would undoubtedly show a greater relative consumption of superphosphate and other inorganic fertilizers, plus large quantities of meal residues. The world-wide use of either mineral or organic fertilizers is largely a matter of availability. Large quantities of meal and mineral fertilizers are manufactured and thus available in this country, while Asiatic fertilization (Hora, 1950; Rabanal, 1950) is limited mainly to the use of locally occurring manures and other organic substances.

Local and regional differences occur in the chemical composition of water and soils. For this reason the selection of fertilizers should be based on the results of chemical analysis of water and soil (Rabanal, 1950; Rounsefell and Everhart, 1953; Schaeperclaus, 1933). An alternative or supplementary method of determining fertilizer requirements is suggested by Schaeperclaus (1933). It consists of inoculating containers of parent water, enriched by various kinds and concentrations of fertilizers with algal cultures. Highest growth rates indicate the most suitable fertilizer and concentration. Swingle and Smith (1939a) used this method with apparent success in early experiments. It has obvious limitations since environmental conditions cannot possibly be duplicated in culture containers. Hasler et. al. (1951), for instance, found that the actual lime requirement for the alkalization of a bog lake was more than three times the quantity estimated by sample inoculation. Availability, cost, and mode of action

with respect to food chains may also influence the selection of fertilizers. Fertilizers are often mentioned in the literature for specific conditions and areas (as Swingle and Smith, 1950; Meehean, 1939).

Fertilizers are generally applied in the spring of the year when waters grow warm and biological activity increases. European consensus (Schaeperclaus, 1933; Lawson, 1937; Wiesner, 1937) is that a single large application of fertilizer suffices, and that additional doses are superfluous. American opinion (exemplified by Swingle and Smith, 1939a, 1950; Zeller, 1952) is that frequent, light doses result in higher productivity and improved conditions. The lack of agreement stems from differences in practice and is significant mainly in fertilizing shallow waters. European fish-cultural methods place greater emphasis on liming (see Fertilization and Pond Culture) and the role of the bottom in pond productivity. Both factions recommend an even distribution of fertilizers over shallow areas. Most fertilizers are dry solids and are distributed as such by broadcasting. Smith (1933), in using this method, produced rapid plankton growth, but a larger total yield resulted when the fertilizer was dissolved from suspended sacks. This possibly may be an important consideration in situations where nutrients are "lost" in the bottom. If a fertilizer consists of several substances, all should be added simultaneously (except caustic lime) to insure proper chemical interaction (Wiesner, 1937).

The theoretical approach of nutrient liberation has been considered by Hasler and Einsele (1948) for the activation of phosphate in eutrophic lakes. It is based on the dissociation of phosphorus and iron and their mutual sedimentation as $FePO_4$ at the fall overturn. Two schemes were presented for the removal of ferrous iron. One is the precipitation of ferrous ions with sulfate; amounts of calcium sulfate needed and the ensuing reactions were discussed. Implications of other nutrient liberations are given by Welch (1935), who noted that magnesium may free calcium and that sodium may release potassium. The cultural practice of draining ponds mobilizes nutrients in accordance with this concept. Since productive increases result in the reduction of bottom soils, draining and aeration cause the oxidation of bound nutrients which, in turn, makes them available the following season. Nutrient release is also one of the major functions of liming (see Fertilization and Pond Culture). This concept holds that chemical elements are limiting, not because of their absence or paucity, but because of their inability to contribute to anabolic processes. It is an approach to artificial fertilization that may be worthy of greater consideration.

Interpretation of Results

Fertilizers act to increase the general productivity of water. The first and most pronounced effects of these nutrients appear on organisms having short life cycles (Ball, 1949). Fish are last to indicate benefits of fertilization, and the quantity produced is the ultimate measure of

fertilizer effectiveness. Time, experimental design, or nature of the environment often necessitates the use of other indices. Moyle (1949) considered several such measures of lake productivity. Quantitative determinations of plankton and bottom fauna, creel returns, fish length and weight increment, relative plant growth, and plankton turbidity are some biological evaluations. Changes in pH may be significant. Surber (1947) and Zeller (1952) suggested that an inverse relation exists between water nitrate and fish growth. Meehean and Marzulli (1945) contended that humus loss and C:N ratio of the substrate may demonstrate fertilizer effectiveness. Their experiments indicated that lowest humus loss and highest C:N ratios were associated with highest productivity. The authors concluded that humus loss is more reliable, while C:N ratios were valuable because of ease in determination. Many of these secondary indexes are valuable at times, and occasionally necessary, but their reliability when applied to fish production is questionable. The many variables in operation subject these indexes to extreme critical evaluation.

Wiebe (1929) described aquatic fertilization as "intentional pollution", implying that it may cause unwanted or, perhaps, detrimental changes. According to Hasler (1947), fertilization involves eutrophication. Many workers have experienced undesirable increases in vegetation, resulting in higher water temperatures and oxygen depletion. Wiebe (1934) pointed out relations between oxygen content and temperature-flora conditions, indicating that reasonable amounts of fertilizer will not cause oxygen depletion so long as vegetation is alive. Measurements for minimal oxygen should be made at dawn (Hogan, 1933). Smith (1934a) noted the extreme chemical and physical conditions tolerated by lower organisms in heavily fertilixed water. Swingle and Smith (1939a) found that ammonium sulfate lowered pH values significantly in moderate to heavy doses, while sodium nitrate tended to increase the hydroxyl-ion concentration. Certain elements (Cu, Zn, As, etc.) are especially toxic to fish in soft waters. Wiesner (1937) cautioned against the use of large amounts of fertilizers containing toxic substances such as cyanide and ammonia. Undesirable effects of fertilization are not limited to chemical toxicity and objectionable flora, but may result from the growth of competitive fish or other injurious fauna.

FERTILIZATION AND POND CULTURE

Fertilization had become a part of Eurasian pond culture long before it was accepted in this country. This early development was stimulated by extensive fish-cultural enterprises and their importance in Eurasian economy. Therein is symbolized the basic difference in fish culture between the two continents. In Europe and Asia, the primary aim of aquiculture is to produce quantities of protein food. Here, most cultural efforts are concerned with a recreational fishery. The European approach to scientific pond fertilization has been meticulous. Consequently, gen-

eral references such as Schaeperclaus (1933) and Wiesner (1937) contain great detail on many phases of pond enrichment. Smith (1932b) considered two cultural concepts of fertilization: (1) Production of zooplankton in greatest possible amounts for removal and feeding to fish; (2) production of food directly in rearing ponds and natural waters. Many early experiments were conducted in accordance with the first concept, mainly because plankton are able to tolerate abnormal amounts of fertilizer. This view has been superseded in recent years by the second concept, the direct fertilization of fish ponds.

The Pond and Enrichment Procedure

Physical characteristics, such as depth, size, and bottom type, exist optimally in the culture pond. Many environmental variables (vegetation, rate of exchange, temperature, sunlight, nutrient loss, and population composition and density) are controllable, often to a large degree. Regulation of the inflow and outflow affects water temperature, oxygen content, and nutrient retention. Pond draining facilitates complete crop removal. Small size and shallowness permits effective seining and control of emergent border vegetation. The latter, in turn, determines the amount of direct sunlight reaching the water. For these reasons, a drainable culture pond represents the ultimate in potential aquatic production.

Advantages of fertilizing such an environment were given by Wiesner (1937): it is less expensive than artificial feeding; the resultant natural feeding causes rapid growth and low losses due to disease and nutritional deficiencies; fish can then tolerate greater population densities. The rearing of brood trout in fertilized ponds, Wiesner added, is uniquely advantageous. Initially there is a plankton bloom upon which fry feed and, as the season progresses, larger food organisms produced correspond to changes in diet of the growing fish. Meehean (1933) further concluded that large fish can be produced at earlier maturity, and the shortened growing season saves space and overhead.

Fertilizers are selected to suit the needs of the pond after consideration is given to the quality of the water and bottom soil. Swingle and Smith (1950) recommended 100 pounds of 6:8:4 and 10 pounds of sodium nitrate per acre-application. Schaeperclaus (1933) suggested using 35 pounds of phosphate (P_2O_5) per acre alone, or with 45 pounds of potash (K_2O). Wiesner (1937) advised similar amounts of phosphate (180 to 270 pounds of superphosphate per acre) as effective and economical. Surber (1947) tabularly listed amounts of some single inorganic fertilizers needed to prepare various N:P:K combinations. A list of fertilizers and the papers in which they were reported is given in the appendix. Fertilizers are spread over the bottoms of drained ponds before spring filling. They are applied to filled ponds by broadcasting from shore or boat over shallow areas. American theory recommends periodic applications throughout the growing season at intervals governed by temperature, plant growth, and oxygen conditions in the water. This may be each 2 weeks in spring and at monthly intervals

during the summer. Smith and Swingle (1941) concluded that winter fertilization of bluegill ponds in the South is inadvisable because of slow fish growth in that season.

The recommendations given here are generalized and may not apply to specific cases. Nelson (1941), for example, found that the addition of fertilizers to shallow areas disturbed spawning beds and hindered the seining of bass fry. This difficulty was eliminated by applying the entire amount of fertilizer to the center of the pond. Rounsefell and Everhart (1953) believed that investigators usually place excessive emphasis on a single factor with the result that recommendations and conclusions concerning pond fertilization vary without reason, and the process reverts to trial and error in different localities.

Techniques Contributing to Maximum Production

Fertilization, although specifically a problem of nutritional chemistry, has other considerations of equal importance. Draining the pond, as previously indicated, oxidizes bottom soils and facilitates crop removal. In addition to these functions, it permits control of aquatic vegetation and competitive or injurious organisms. Ponds are usually drained at the end of the growing season and are allowed to overwinter in fallow (Schaeperclaus, 1933). Nutritionally poor bottoms may be seeded with a legume in early spring and the crop plowed into the soil when in bloom.

Liming is considered the first step in pond fertilization (Schaeperclaus, 1933; Wiesner, 1937). Strictly speaking, it concerns the addition of caustic lime (quicklime, slaked lime, or calcium cyanamid (see Appendix A) to the pond bottom when in spring fallow. Liming serves the following purposes:

1. Kills, by caustic or caustic and toxic action, the eggs and intermediate stages of fish parasites and some plants.

2. Raises the pH of water to a level most favorable for fish health and metabolic cycles of the pond.

3. Raises the A.C.C. of the water and creates a carbon-dioxide reserve.

4. Insures sufficient calcium for plant and animal nutrition; for the building of carapaces and shells; and for the detoxification of soluble sodium, magnesium, and potassium compounds.

5. Ameliorates the bottom (aids mineral decomposition, liberates potassium, hastens soil decomposition, lowers oxygen consumption).

6. Eliminates strong excesses of putrescible organic matter (which demand oxygen and provide favorable conditions for the existence of many disease instigators).

Liming is preferably done about 2 weeks before the addition of fertilizers, to avoid binding nutrients in insoluble calcium compounds. The degree of caustic action desired, and the activity of the soil vary the dosage from 90 to 350 pounds per acre. Liming, in a more general sense, covers the addition of noncaustic lime compounds (limestone, lime marl) which may accomplish all purposes except the first. Such lime may be included with the fertilizers. Sandy bottoms and calcium-rich waters may derive little benefit from liming.

Proper stocking, as to species composition and numbers, is essential for maximum productivity. Stocking tables can be found in the literature:

Schaeperclaus (1933) . . . comprehensive
Wiesner (1937) . . . . . . salmonids
Swingle and Smith (1950) . pondfish

The fishes involved in fertilization work are listed in the appendix with references to the papers in which they appear. The total yield of fish per unit area varies, as does stocking density, with species and population composition. Generally, productive increase in enriched ponds is reckoned at 100 percent over unfertilized ponds. This may be expected to vary considerably in different geographical locations and with different types of fish. It is readily understandable why omnivorous carp can be produced in greater quantity than can carnivorous fish such as bass. Maximum yields of carp and related species in Asiatic countries, as cited by Hora (1950), generally range from 2,000 to 4,000 pounds per acre per year. On the other hand, Swingle and Smith (1950) claimed that fertilized Alabama ponds produce 400 to 600 pounds of sport fish per acre compared with 40 to 200 pounds per acre in unfertilized ponds. Properly fertilized waters in our northern latitudes may show only 30-percent increase over control ponds because of the shorter growing season.

Conclusions on Pond Fertilization

Experiments in pond enrichment have generally revolved about the testing of common fertilizer types and concentrations relative to the production of food organisms and various species of fish. In these trials, near-isomorphic ponds have been used as typical test and control units. Some experimental work, of course, has not followed this pattern. Henderson (1949) tested the value of manganous sulfate as a plant stimulator, and was apparently successful in producing the desired algal blooms with concentrations of 0.1 and 1.0 part per million. Walker (1949) failed to increase production by adding limestone to acid ponds. Weed control by fertilization has been an interesting sidelight. Surber (1945) found that hay plus superphosphate effectively controlled overabundant flora. Organic and organic-plus-superphosphate fertilizers produce heavy algal growths which can be destroyed by sodium-nitrate applications, according to Smith and Swingle (1943). Patriarche and Ball (1949) were unable to control algae as suggested by these authors. Productive increases of fish have

not always been attained, as shown by Ball (1949), who increased the abundance of plankton and bottom fauna without significantly affecting the fish yield.

Implications which may be drawn from piscicultural literature resolve the subject of pond fertilization into two components:

1. Cultural aspect. A culturist need only have the fertilizers, ponds, fish and the objective of fish production. Fertilizers are applied in advised amounts according to recommended procedure. Results will vary, but by altering the type and quantity of fertilizers the culturist will arrive at increased yields of some consistency within a few years. When the increased production overbalances the cost of fertilizers and fertilization, success is achieved. Knowledge of pond metabolism is not essential, nor is it useless. An understanding of the causes and effects of changes due to nutrient addition will enable the culturist to produce more fish at less expense and with greater consistency.

2. Experimental aspect. This is explained and related to the above by Meehean (1939,p.1). Referring to the culturist's view of scientific investigation, he stated, "They (culturists) are not conscious of the fact that results from such a study are dependent upon the vagaries of nature and not produced at will as a series of chemical experiments might be. It has not been realized that many problems such as the social reactions of the fish, how they feed, how the food organisms are produced, what food chain from the organic compounds to fish is the most beneficial, what fertilizer will best stimulate this food chain, must first be solved in order to know what is happening. In other words, one must get to the fundamentals of the reactions of the fishes and their relation to food in order to offer an intelligent solution to the problem. We are still a long way from that final solution." Other problems more intimate to nutritional enrichment, might be added to Meehean's list. The solutions have not yet been compounded and remain to be reached only through careful experimentation. Therein lies the need for experimental fertilization.

Piscicultural trends in the United States are directed toward sport-fish production and, since protein food is abundant, no serious efforts have been made to produce food fish. The phenomenal annual yields of 1 to 2 tons per acre found in European and Asiatic carp culture cannot be expected under our cultural methods. The ecology and food habits of our sport fish, together with the cost of fertilization, limit the extent to which this method of production gain applies. Rounsefell and Everhart (1953), considering the use of commercial fertilizers, estimated the cost of fertilizing shallow ponds at 15 to 20 dollars per acre per year. At that rate, without complete assurance of satisfactory results, artificial enrichment may not be profitable. Present needs seem to call for the development and standardization of fertilization methods in pond culture, rather than the promotion of fertilization as now practiced.

FARM FISH PONDS

A great deal of literature has been published in recent years on the construction, maintenance, and management of farm fish ponds. Apparently the public has been convinced of their practical, recreational, and conservational value. In response to such publicity, innumerable farm ponds have appeared in various parts of the country. Fertilization is one of the management practices commonly recommended and much pioneer work to that end has been done in Alabama by H. S. Swingle and his collaborator, E. V. Smith. Several of their reports are cited in the "List of References".

A discussion of farm fish ponds as environmental entities related to artificial enrichment is felt unnecessary because such treatment would merely overlap the preceding and subsequent sections of this report. Information gleaned from farm-pond literature has already been presented and the reader is referred to those publications for more direct and pertinent data.

One important issue, the practical value of fertilizing farm ponds, is open to question. One might assume, after reading some of the literature, that fertilization is an essential phase of proper farm fish pond management. However, fish rearing in farm ponds is not intensified as in culture ponds, nor is it done for a marketable crop. Published reports do not indicate the extent of harvest in farm ponds, but it is probable that few of them are adequately cropped. Therefore, unless serious effort is made to harvest the fish, it seems unwise to recommend the fertilization of farm ponds where costs are involved.

FERTILIZATION OF LAKES

Thus far, specific discussion of aquatic environments has been mostly limited to drainable culture ponds. Delicate experiments in aquatic nutrition have been conducted in laboratory containers where many natural variables can be eliminated or controlled. Much fertilization literature is devoted to farm fish ponds, and some to trials in lake enrichment. These different types of lenitic habitats can be arranged in a sequence of increasing environmental complexity, paralleled to a large extent by increasing size and depth. The simplest is a laboratory receptacle, followed by outdoor pools, drainable culture ponds, nondrainable culture ponds, farm fish ponds and natural ponds, small shallow lakes, and, finally, larger lakes of increasing physical and biological diversity. Notable changes occur in this progression when it is considered from an enrichment point of view. The first appears when the artificial retaining structure is replaced by natural soil. A second important break exists between drainable and nondrainable waters. A third of probable importance coincides with thermal stratification. The second and third major changes in the nutritional succession indicate basic differences between culture ponds and lakes so far as this paper is concerned, and will be considered with other factors in the following sections.

The Environment and Artificial Enrichment

Ponds and lakes differ in size, depth, and degree of control that can be exerted over many variables. Increasing size and depth imply decreasing productive capacity (relatively), and decreasing economic feasibility for fertilization (Hasler, 1947; Smith, 1952). There are obvious limitations in depth and area of a fertilizable lake. The inability to control several important factors is also discouraging. Added nutrients may be carried away in lakes having a rapid rate of exchange. Affluents may bring allochthonous nutrients into a lake in beneficial quantities, but may also carry toxic substances and excessive nutrients to cause eutrophication. Most lakes cannot be drained to derive the many benefits attributable to that process.2/ Plant and animal populations are established, and controllable only to a limited extent. This is disturbing in that the populations not only affect fertilization, but may be affected by it in various and sometimes undesirable ways. Fluctuations in abundance of organisms irrespective of enrichment are difficult to fathom, and insert a question into the interpretation of fertilizer effects. Finally, the crop removal is rather indefinite, being subject to the pressure and effectiveness of angling.

Thermal stratification, for purposes of fertilization, divides a lake into a trophogenic epilimnion and an oxygen-deficient, tropholytic hypolimnion which may entomb nutrient elements by permanent sedimentation. Hutchinson and Bowen (1947) found that 47 percent of the phosphorus introduced into a small lake had descended below the thermocline before it could be utilized in the biological cycle. The fall overturn serves to disperse oxygen and dissolved substances throughout the lake, and thus reverse the tropholytic processes occurring in the hypolimnion during summer stagnation. However, it may also cause the precipitation and consequent loss of valuable nutrients. The spring overturn acts similarly, but since it follows mild winter activity, nutrient loss is not as great. The subsequent warming of water in the presence of abundant nutrients causes increasing biological activity. The thermocline, then, is significant because it diverts or consumes many nutrients which would otherwise contribute to the productive metabolism of the lake.

It would seem desirable here to discuss lakes in the common (but somewhat arbitraty) grouping of oligotrophic, eutrophic, and dystrophic. By doing so, many related chemical, physical, and biological factors could be considered in conjunction with results of lake-enrichment attempts. However, supporting data in reports of lake fertilization are not detailed enough to warrant this distinction. Reports are summarized below in two groups: lakes supporting warm water fishes (warm-water lakes), and lakes supporting salmonids (cold-water lakes). Herein the separation is purely mechanical; it may be of significance when more lake experiments have been

2/ Certain impoundments are capable of being drained. In such circumstances, an increase in productivity has been noted after dry fallow, refilling, and restocking.

performed. This division is based on the general contentions that warm-water fishes can tolerate greater population densities and physico-chemical extremes; that warm-water fishes occur in lakes of higher temperature which signify higher metabolic rates and, perhaps, greater productivity; and that, other things being equal, warm-water fishes respond more readily to fertilization.

Experiments in Lake Fertilization

Pioneer work in scientific lake enrichment was done by Juday et al. (1938) on a 39-acre, 44-foot (maximum) depth, seepage lake containing smallmouth black bass and yellow perch. Various fertilizers were added over a 5-year period as follows: 1932, superphosphate; 1933, superphosphate and lime; 1934, superphosphate, lime, and ammonium sulfate; 1935, potassium chloride and cyanamid; 1936, soybean meal. The effects were studied in terms of dissolved ions, plankton quantity, and growth rates of perch. Initially, the water was "very soft" (0.7 parts per million calcium). Added nutrients raised the water levels of phosphorus, nitrate, and calcium, but only the latter remained above prefertilization level. Plankton content and perch growth did not change significantly until after the 1936 fertilization, whereupon a sharp increase was noted in both. These biological indexes continued high the following year and the authors concluded that organic matter was more effective than mineral fertilizers used singly or in groups. Therefore, the organic content of the lake appeared to be limiting.

King (1943) reported the fertilization (6:9:3 and sodium nitrate) of a shallow, acid (pH 5.2 to 7.0), 21-acre lake containing largemouth bass, bluegill, and several types of coarse fish. Productive changes were studied in terms of fishing returns (average catch per hour, average creel weight, and pounds per acre caught). Comparison of these indexes before and after fertilization showed a decrease in fishing returns, but the drop was not as great in the fertilized lake as in a nearby control lake. Ball (1950) and Ball and Tanner (1951) fertilized one of two adjacent shallow seepage lakes containing several species of warm-water fish. Inorganic 10:6:4 was added at 3-week intervals, May to mid-September, at the rate of 100 pounds per acre, in 1946 and 1947. Definite plankton gains followed each application and growth rates of game fish showed significant increase. Heavy algal mats, which restricted spawning, formed during the second summer. Neither lake had experienced a winterkill within 10 years before fertilization, but anaerobic conditions under a winter icecap caused the destruction of most fish and insect life in the fertilized lake following the second year of nutrient addition. The fertilized lake was restocked in 1948 and the fish grew rapidly. Filamentous algae presented no further problem, and plankton blooms did not occur in the ensuing summer. Surber (1948) successfully fertilized a 44-acre recreational lake with 5:10:5 and lime, to control nuisance excesses of submerged aquatic plants. It was also noted that fishing improved.

More cold-water lakes have been fertilized than the above-mentioned warm-water lakes. Perhaps this is because they are "poorer producers", lower in mineral solutes, and therefore considered better enrichment potentials. A superficial fertilization of the centrally located lake in a chain of three, with 15 tons of sea mussels, was reported by Smith (1931). Marked plankton increases in the fertilized lake, and in the lake below it, were noted the following year. Taylor (1944) discussed the fertilization of a clear-water, sand-bottom trout lake with 4:8:10 plus calcium carbonate, indicating a large increase in trout weight attributed to fertilization. The content of these reports does not justify more than passing comment.

One phase of a trout investigation project, reported by Wales (1950), involved the organic enrichment of a clear, deep (120 feet, maximum), alpine oligotrophic lake supporting four species of salmonids and some forage fish. Pretreatment water analysis showed 34 parts per million total dissolved solids, a hardness of 23 parts per million, and a pH near neutrality. Cottonseed meal was selected on the basis of promising results shown by Juday et al. (1938). The only apparent change was an increase in turbidity immediately following fertilization. Langford (1950) fertilized four deep lakes, thermally stratified, with inorganic 12:24:12 at monthly intervals. This preliminary report considered detailed changes in plankton abundance. A definite increase in phytoplankton occurred within 3 weeks to 1 month after nutrient application, and it appeared that only a single spring addition was utilized by these organisms. In conjunction with the fertilization of a warm-water lake (discussed above), Ball (1950) reported the artificial enrichment of one of a pair of sand-bottom trout lakes. As in the warm-water lake, excessive summer growth of algae fostered winter anaerobiosis which caused the death of fish and insects in the fertilized lake.

The fertilization study of a shallow, soft-water lake containing brook trout and four species of rough fish was made by Smith (1948a, 1948b). A single application of ammonium phosphate and potassium chloride in late spring caused a zooplankton bloom which disappeared later in the season during a bloom of Anabaena. Postfertilization observations within the same year showed an increase in bottom fauna, oxygen saturation, and carbon-dioxide reserve over prefertilization levels. Water phosphorus remained somewhat above normal during the season. Indications of increased trout growth and angling success were obtained the following season (1947) when the yield of trout to anglers (3.6 pounds per acre) more than doubled the average returns for a 2-year period before nutrient addition. This was attributed to catches of rapidly growing stock fish (60 percent of total catch) which previously grew slowly and constituted only a small part of the creel returns. Observations in the succeeding years (Smith, 1952) showed a decline in fishing returns. The author concluded that further benefits to trout were masked by predators which also profited from the nutrient enrichment, and that predator control plus a supply of trout to capitalize on the increased food supply are requisites for successful fertilization.

The alkalization of two brown-water bog lakes has been reported recently by Hasler et al. (1951). Objectives of this investigation were to neutralize the acidity (pH 5.4 to 5.6) and increase light penetration by the precipitation of humic colloids as lime humate. The addition of limate and calcium carbonate to the water brought pH to neutrality, increased the carbon-dioxide reserve, light penetration, total phosphorus, and organic nitrogen, while the ammonia and nitrite nitrogen, iron, and sulfate content were decreased. These effects were more pronounced in the lake that received heavy lime applications early in spring than in the one that received prolonged applications throughout the summer. Cost was about 60 cents per acre-foot.

Shortcomings are evident in these lake-fertilization reports. In general appraisal of work done, it might be said that treatment preceded diagnosis. Pretreatment data, necessary for the interpretation of fertilizer effects, were weak and insufficient. Post-treatment observations were more numerous and carefully done, but were not of the quality and quantity demanded by the situation. Proper consideration was not given to the many variables that affect the intricate mechanism of nutrient enrichment. Thus, conclusions reached were often either assumptive, or too broad to contribute information of significance.

Conclusions on Lake Fertilization

Similarities occur in the effects of fertilizers in lakes and in ponds, as might be expected. Population increases were rapid and most pronounced among the lower organisms. Single species, rather than whole groups, tended to show greatest gains. Nutrients disappeared rapidly from solution, apparently through deposition in bottom soils and uptake by living organisms. Lake-fertilization results differed from those of ponds in that less noticeable changes occurred after the addition of nutrients, especially to fish life. The effects of fertilization on fish were not included in the reports of Smith (1931), Langford (1950), and Hasler et al. (1951). Fish did not benefit from the first 4 years of lake enrichment described by Juday et al (1938), or in the experiments performed by Ball (1950) and Wales (1950). Nutrient applications were of questionable value to fish in two cases (Juday et al., 1938; King, 1943), while Taylor (1944) and Smith (1948b, 1952) indicated definite growth increases. All in all, fish may have profited from fertilization in one warm-water and two cold-water lakes. The biological destruction of two lakes by the artificial enrichment described by Ball (1950), and Ball and Tanner (1951) demonstrates a possible pitfall in tampering with the natural metabolism of lakes. Perhaps there have been other negative attempts at lake fertilization which, although noteworthy at this time, have not been reported. In concluding the various results, it can be said that fertilization increases at least part of the productive capacity of lakes, but not necessarily the yield of fish. It is possible that fertilization may become a valuable technique in raising the productive levels of some lakes, and an important method of studying the biological interactions and little-known chemical relations of lakes in general.

The practical success of artificial lake enrichment demands a consistent increased yield of desirable fish to angler. Assuming that productive capacity of a lake can be enhanced by fertilization, it is necessary to examine the possible effects of fertilizers on the principal objective. Some concepts of increased productivity, based on hypotheses in Province of Quebec (1948), which do not insure practical success are--

1. A general increase in the abundance of plants and animals to the extent of complete eutrophication, and resulting destruction of the fish population.

2. A decrease in the population of desirable fish owing to overcrowding by excessive growth of submerged flora.

3. A decrease in total population of desirable fish by the gain of a few large cannibalistic individuals, or by increase in the population of coarse fish.

4. An increase in population of desirable fish with individuals too small to be utilized.

5. An increase in population of desirable fish with individuals of usable size, but a lower yield to anglers caused by excessive natural food or difficulty in angling (surface blooms, littoral vegetation).

Other concepts could be added to this list but it is intended solely to indicate effects which deserve consideration in the planning of a lake-fertilization program, and in the interpretation of results. A hypothetical situation demonstrates the flaws in some conclusive reasoning. Suppose that a lake containing a population of undersized fish was fertilized to increase the size of its fish. Due consideration was given to several chemical and biological factors. Fertilizers were selected and applied according to recommended procedure. Post-treatment determinations showed improved chemical conditions and a general increase in plant life, nannoplankton, benthos fauna, or other indexes used in the study. Fish growth was carefully watched but, alas, there was no change. Although the number of fish may have increased owing to conditions which allowed a greater population density, the investigator erroneously concluded (on the strength of his data) that no benefit to fish resulted from the addition of nutrients.

A lake is a sizable and complex environment, often reacting independently or adversely to efforts in its management. The fertilization of a lake poses an impressive problem. Cost of enrichment, in terms of net fish yield, may be prohibitive; this is especially true of deep oligotrphic lakes. Experience gained from pond fertilization shows that a single application will not keep productivity high indefinitely. Rather, fertilization requires the renewal of nutrients at least annually, especially if the crop is regularly removed. What, therefore, is the basis for the artificial enrichment of a lake? The stimulus must be either an explicit

demand for more fish or the need for more knowledge of lake metabolism. Considering the low degree of success in past lake-enrichment attempts, the demand for greater fish crops through lake fertilization is seemingly inadequate to justify the process in this country at present. If artificial enrichment is to be applied to the study of lake metabolism, experimental designs must be more rigid than those used in past investigations in order to procure results of greater significance. Hasler and Einsele (1948) stressed the importance of scientific approach to lake fertilization. A thorough limnological investigation should precede enrichment. A few lakes should be tested over a number of years, or several proximate lakes in a shorter time. Inherent variations in chemical and biological constituents among the lakes, and normal fluctuations of these factors within each lake must be considered. The experiment should then test a minimum number of factors in such a manner that the results will be clear and will lend themselves to statistical interpretation.

SUMMARY

1. Artificial enrichment and the environmental factors associated with it are treated in order to describe the fertilization processes and relate them to various fields of fresh-water fisheries. The literature reviewed is largely North American, but pertinent Asiatic and European reports are included.

2. The fertilization mechanism involves many physical, biological, and chemical factors which are complex and interrelated in the aquatic habitat. Recognition of such factors is essential to sound planning and interpretation of enrichment experiments.

3. Heat, light, and dimension are the most important physical considerations. The first two function mainly in photosynthetic activity, upon which rests the fate of higher fauna. Heat and light exposure of the water are limited by geographical variation in growing season, occludent vegetation, and turbidity. Small size and shallowness of the environment signify greater relative productivity.

4. Biological components of a lake or pond may be classified as either producers (flora and microfauna) or consumers (macrofauna) and form various food chains from nutrient matter to removable fish crop. A fertilization program should consider such successions and operate through the most direct route to fish production. Organisms that do not contribute to the success of enrichment should be suppressed. Bacteria are of singular importance in bridging the gap between nutrient matter and other organisms. Fluctuations in abundance, a characteristic of plant and animal populations, may result from or occur

independent of fertilization. The objective of artificial enrichment is productive increment, considered here in terms of yield of desirable fish per unit area and time.

5. Chemical considerations of the environment concern the presence and reactions of nutrient elements or compounds, and their relations to living organisms. Since the substrate is chemically and biologically active in shallow water, fertile soils signify high productivity. Productive waters are generally rich in dissolved substances and have an alkaline pH (7.0 to 8.5). Many chemical elements are required for the sustenance of life but only four (nitrogen, phosphorus, potassium, calcium) and organic matter have been widely used in aquatic fertilization. Whether these elements limit productivity is a controversial matter, but most authorities agree that phosphorus is usually limiting in natural waters, and is the most valuable fertilizing element.

6. Phosphorus functions as an assimilator of nitrogen into cellular material. It occurs naturally in a dynamic state, the dissolved component (organic and phosphate phosphorus) being smaller in quantity with a consequent faster turnover rate than the phosphorus in solids. Soluble phosphate is absorbed directly in a matter of minutes by lower organisms, and can be concentrated in large amounts by fauna. Since it is an active element, phosphorus may combine with iron or calcium and be lost by permanent sedimentation of insoluble phosphates.

7. Nitrogen, a constituent of protein, is found free and combined (NH_3, NO_2, NO_3, and organic nitrogen) in the water. These forms of nitrogen are related in a cycle energized by bacterial activity. Nitrate is generally regarded as available nitrogen, but lower organisms may also utilize nitrite and ammonia nitrogen.

8. Calcium and magnesium function similarly in the complex carbon-dioxide mechanism of the water. Individually, calcium is the more important element, often the major precipitate and dissolved cation in waters draining lime-rich soils. It functions physiologically in plant tissue, is a prominent structural member in faunal groups, and, in general, ameliorates chemical conditions in the environment. Magnesium is not so abundant, but is necessary for chlorophyll production and may aid bacterial reduction in the substrate.

9. Potassium is the most beneficial of the remaining elements, especially to submerged flora. As a fertilizer, its effects are indirect and selective, and its reactions are most favorable in bottoms of peat or sand. Functions of other mineral elements are discussed.

10. Organic matter is necessary for a high productive capacity. It occurs in solution, in suspension, and deposited in the bottom. These complex compounds result from excretory processes and decomposition of plant or animal matter. They are the source of energy for bacteria and become transformed into usable nutrients by the saprophytic action of such organisms. The ratio of carbon to nitrogen has been related to levels of bacterial activity.

11. The addition of nutrients to directly increase production is the common approach to aquatic fertilization. It concerns the selection and application of mineral or organic fertilizers to best suit environmental needs, in order to attain highest productivity. Availability, cost, amount, mode of action, method, and periodicity of application of fertilizers are factors to consider. A second approach considers nutrient limitations due to unavailability. This theory operates in the fish-cultural practices of draining and liming, which mobilize nutrient materials held by chemical retention in reduced bottom soils or inactivation due to adverse environmental conditions. As a direct approach, nutrient liberation exists only in theory.

12. Fertilizers cause a general increase in water productivity, and various indexes (both biological and chemical) have been applied to measure their effects. Such measurements are subject to the vagaries of man and nature, and must be viewed critically. Enrichment may not aid the desired end of fish yield because of undesirable changes (lowered pH, toxicity, oxygen depletion) or diversion of nutrient matter into nuisance animal and plant growths.

13. Factors affecting fish yield, such as sunlight, temperature, rate of water exchange, fish populations, and plant growths, are controllable to a certain extent in a culture pond. Control plus optimum dimensions result in high productive capacity and render such ponds very profitable for fertilization. Cultural fertilization is said to be more economical than artificial feeding, the natural nutrition enabling greater population density and resulting in hardier fish. Recommendations as to type and quality of fertilizer for general enrichment can be found in the literature, but do not apply in all instances. Nutrients are added before or during the growing season and must be renewed at least annually to sustain yields.

14. Draining, liming, and proper stocking should be considered in order to realize the greatest productive effects of fertilization. Draining facilitates crop removal and control of undesirable plants or animals. Winter fallow oxidizes bottom soils, thereby activating nutrient substances. Liming, strongly recommended by European culturists, kills disease instigators; raises

buffer effect and pH of water; provides calcium for nutrition; and aids in detoxification, amelioration, and nutrient release. Correct stocking as to species composition and number is essential. Proper fertilization and accessory techniques usually boost fish yields to 100 percent or more over unfertilized ponds.

15. The numerous pond-fertilization reports duplicate or parallel each other in many instances, but indicate two aspects of pond enrichment. Cultural fertilization deals strictly with production of fish by varying the type, quantity, and rate of application in order to arrive at consistently high yields. Experimental fertilization considers intricate problems of hydro-chemistry and biota-nutrient relations which can be explained only through careful experimental studies.

16. Sport-fish yields from cultural efforts in this country, comparable to the high production of food fish from fertilized Asiatic and European ponds, cannot be expected. High cost of fertilization and lack of assured success call for the development of better enrichment techniques in our pisciculture.

17. Farm fish ponds are not discussed in detail, to avoid repetition of information considered elsewhere in the report. Since these ponds are established for a recreational fishery and may not be cropped properly, a question is raised about the practical value of fertilization involving cost.

18. As aquatic habitats increase in size and depth, they become more complex and less practical to fertilize. The average fish yield in lakes is only a fraction of that in culture ponds. Besides dimensional drawbacks, features of lakes that discourage fertilization are lack of control, established populations, nondrainability, thermal stratification, and indefinite harvest.

19. Conclusions drawn from 11 lake-fertilization trials indicate that fish may have benefited from enrichment in only three experiments. Effects of fertilization were more pronounced on lower organisms, especially single species of plankton. Stimulated growths of waterflora have caused winterkill upon decay. Although the fertilization of lakes has increased their productive capacity, its practical success in terms of net fish yield to anglers is doubtful. End effects of lake enrichment must be viewed cautiously with regard to the many variables of the environment.

20. Sport-fishing returns of lakes are not comparable in monetary value to the yield of fish flesh in pond culture. Lake fertilization, at present, can be a method of studying water metabolism with results possibly applicable to a future program of enrichment that would raise the productive capacity of some lakes. If clear-cut, significant data are to be obtained, such scientific studies need sound experimental design.

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APPENDIX A

FERTILIZERS REPORTED IN THE LITERATURE

Inorganic

Ammonium phosphate: Smith (1948a, 1948b, 1952).

Ammonium sulfate: Juday, et al. (1938), Schaeperclaus (1933), Smith and Swingle (1940, 1941), Swingle and Smith (1939a), Surber (1947), Wiesner (1937).

Basic slag: Lawson (1937), Smith and Swingle (1940,1943), Swingle and Smith (1939b).

Bone meal: Davis and Wiebe (1930), Lawson (1937), Schaeperclaus (1933).

Caustic lime: Hasler and Einsele (1948), Lawson (1937), Neess (1949), Schaeperclaus (1933), Wiesner (1937).

Colloidal phosphate: Meehean and Marzulli (1945).

Cyanamid, calcium cyanamide: Juday et al. (1938), Schaeperclaus (1933), Wiesner (1937)

Dicalcium phosphate: Lawson (1937), Schaeperclaus (1933).

Limate: Hasler et al. (1951).

Manganous sulfate: Henderson (1949).

N:P:K: combinations: Ball (1949, 1950), Ball and Tanner (1951), Brown (1951), Hasler and Einsele (1948), Henderson (1949), Hogan (1933,1949), King (1943), Langford (1950), Leach (1936), Meehean (1935), Patriarche and Ball (1949), Surber (1945, 1947, 1948), Swingle and Smith (1939a, 1941, 1950).

Noncaustic lime: Hasler and Einsele (1948), Hasler et al. (1951), Juday et al. (1938), Lawson (1937), Meehean and Marzulli (1935), Neess (1949), Schaeperclaus (1933), Smith and Swingle (1941), Surber (1948), Swingle and Smith (1939a, 1941), Swingle (1947), Walker (1949), Wiesner (1937).

Potash, potassium salts: Hasler and Einsele (1948), Juday et al. (1938), Lawson (1937), Schaeperclaus (1933), Smith (1948a, 1948b), Smith and Swingle (1941), Surber (1947), Swingle and Smith (1939a, 1939b, 1941), Wiesner (1937).

Rhenania phosphate: Neess (1949), Schaeperclaus (1933), Wiesner (1937).

Sodium nitrate: Hogan (1949), King (1943), Meehean (1939), Meehean and Marzulli (1945), Schaeperclaus (1933), Swingle and Smith (1939a, 1941, 1950).

Superphosphate: Brown (1951), Davis and Wiebe (1930), Hasler and Einsele (1948), Hogan (1933), Juday et al. (1938), Lawson (1937), Meehean (1939), Neess (1949), Schaeperclaus (1933), Smith and Swingle (1940, 1941, 1943), Surber (1945, 1947), Swingle (1947), Swingle and Smith (1939b), Wiebe (1929, 1934), Wiesner (1937).

Thomas meal: Schaeperclaus (1933), Wiesner (1937).

Organic

Aquatic plants: Hasler and Einsele (1948), Meehean (1935), Schaeperclaus (1933), Swingle and Smith (1950), Wiesner (1937).

Cottonseed meal: Hogan (1933), Leach (1936), Meehean (1933, 1935, 1939), Meehean and Marzulli (1945), Neess (1949), Smith and Swingle (1940, 1943), Surber (1945, 1947), Swingle (1947), Wiebe (1934)

Fish meal: Leim (1934), Schaeperclaus (1933), Smith (1931, 1933, 1934b, 1934c, 1936, 1938).

Hay: Meehean and Marzulli (1945), Surber (1945, 1947).

Manure: Davis and Wiebe (1930), Hiyama (1950), Hora (1950), Leach (1936), Meehean (1933, 1939), Nelson (1941), Schaeperclaus (1933), Shelubsky (1950), Surber (1945, 1947), Swingle (1947), Wiebe (1929), Wiesner (1937).

Peanut meal: Smith and Swingle (1943).

Poultry laying mash: Smith and Swingle (1940, 1943).

Sea Mussels: Smith (1930, 1931).

Shrimp bran: Wiebe (1929).

Soybean meal: Davis and Wiebe (1930), Juday et al. (1938), Leach (1936), Meehean (1933), Neess (1949), Smith and Swingle (1943), Surber (1945), Wales (1946), Wiebe (1929).

Miscellaneous: Embody (1921), Hora (1950), Lawson (1937), Leach (1936), Meehean (1939), Prince and Bear (1943), Schaeperclaus (1933), Smith (1933), Swingle (1947).

APPENDIX B

FISH AND FOOD ORGANISMS REPORTED IN THE LITERATURE

Largemouth bass: Ball (1949), Brown (1951), Hogan (1933), King (1943), Leach (1936), Meehean (1933, 1934, 1939), Meehean and Marzulli (1945), Nelson (1941), Patriarche and Ball (1949), Smith and Swingle (1940, 1943), Swingle and Smith (1950).

Smallmouth bass: Ball (1950), Juday et al. (1938), Surber (1945, 1947), Swingle and Smith (1939).

Bottom fauna: Ball (1949), Ball and Tanner (1951), Howell (1942), Patriarche and Ball (1949), Smith (1948a), Wales (1946).

Bullhead, catfish: Ball (1950), Brown (1951), Swingle and Smith (1939a, 1950).

Carp and allied fishes; Hiyama (1950), Hora (1950), Lawson (1937), Probst (1950), Rabanal (1950), Schaeperclaus (1933), Shelubsky (1950), Snieszko (1941).

Forage fish (minnows, suckers, etc): Ball (1949), Meehean (1939), Schaeperclaus (1933).

Panfish (bluegill, crappie, etc): Ball (1949, 1950), Ball and Tanner (1951), Brown (1951), King (1943), Patriarche and Ball (1949), Smith and Swingle (1940, 1941, 1943), Swingle and Smith (1939a, 1939b, 1950).

Perch, pikeperch: Ball (1950), Ball and Tanner (1951), Juday et al. (1938), Schaeperclaus (1933).

Plankton: Ball (1949), Ball and Tanner (1951), Henderson (1949) Juday et al. (1938), Langford (1950), Leach (1936), Meehean (1934), Smith (1931, 1932a, 1933, 1948a), Smith and Swingle (1940), Swingle (1947), Swingle and Smith (1939a, 1939b), Walker (1949), Wales (1946), Wiebe (1929, 1930).

Trout: Ball (1950), Smith (1936, 1938, 1948b, 1952), Taylor (1944), Wales (1946), Wiesner (1937).

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